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ANTIMATTER PROPULSION: STATUS AND PROSPECTS

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ABSTRACT

The use of advanced propulsion techniques must be considered if the currently envisioned launch date of the manned Mars mission were delayed until 2020 or later. Within the next 30 years, technological advances may allow such methods as beaming power to the ship, inertial-confinement fusion, or mass-conversion of antiprotons to become feasible. A propulsion system with an ISP of around 5000 s would allow the currently envisioned mission module to fly to Mars in 3 months and would require about one million pounds to be assembled in Earth orbit. Of the possible methods to achieve this, the antiproton ($\bar{p}$) mass-conversion reaction offers the highest potential, the greatest problems, and the most fascination. Antiprotons are currently being produced in the world at the rate of about 10^{14} particles per year. Based on the past 30 years of production experience, antiproton production rates have increased by an order of magnitude every 2.5 years. If this trend continues, almost a mg/yr (6×10^{20} particles) could be produced by the early 2000's. To accomplish this level of production, significant progress needs to be made in accelerator technology. Increasing the production rates of antiprotons is a high priority task at facilities around the world. Rapid progress can be expected in the shorter term. Antiprotons are currently stored in large synchrotron rings. By lowering the particle energy, storage can be achieved in compact structures known as ion traps. Current experiments plan to decelerate and capture up to 10^{10} antiprotons in such as trap. The storage capability of ion traps is limited. However, these traps will provide a source of sub-thermal $\bar{p}$'s for development of better storage mechanisms suitable for propulsion. The application of antiprotons to propulsion requires the coupling of the energy released in the mass-conversion reaction to thrust-producing mechanisms. In addition, there are recent proposals which would enhance the average energy released per $\bar{p}$ used. These proposals entail using the $\bar{p}$'s to produce inertial confinement fusion or to produce negative muons which

can catalyze fusion. By increasing the energy released per $\bar{p}$, the effective specific cost, (dollars/joule) can be reduced. These proposals and other areas of research can be investigated now. These short term results will be important in assessing the long range feasibility of an antiproton powered engine.

INTRODUCTION

The type of propulsion system used on Mars missions may depend on when a particular ship is launched. If the mission is launched later than around 2010, several currently envisioned advanced propulsion concepts may be feasible and could be utilized for improved mission performance.

An advanced propulsion system would offer the potential for reducing (1) the required total ship mass to be assembled in Earth orbit for a given payload mass; (2) the total amount of material and the costs of launching the material from Earth's surface to orbit; and (3) the round trip transit time from years to a few months.

Within the next 30 years, technological advances may allow systems with a specific impulse (I_{sp}) of 2000-5000 s and with thrusts of around a meganewton to be developed. The effects that such a system could have on a Mars mission are shown in Table 1. To duplicate the baseline mission profile of 360 days outbound-260 days return for a 100 ton payload, about 220 metric tons of mass would be required in Low Earth Orbit (LEO). By comparison, the chemical propelled system (LO_2/LH_2) would require about 1800 metric tons. If a shuttle based delivery system is used, i.e. 65,000 lbs/launch, the LEO mass requirements imply 61 launches for the chemical system compared to 8 launches for an advanced propulsion system.

In addition to the tremendous reduction of the required LEO mass, high I_{sp} systems also offer the possibility of faster transit times. The LEO mass requirements for a 1 yr round trip mission and a 6 month round trip time are also shown in Table 1 and are about 308 metric tons and 422 metric tons, respectively. Thus, a round trip time of 6 months could be accomplished for less total mass than is currently estimated for the chemically propelled 680-day mission.

The reduced trip time may be necessary in view of the physiological and psychological responses of the Russian cosmonauts after 239 days of weightlessness. If less than 100 days of weightlessness were endured, a

TABLE 1

MARS MISSION

Mass Comparison (Klbs)

	Chemical Propulsion	Case 1[a]	Case 2[b]	Case 3[c]
EOI				
Payload	112.69	112.69	112.69	112.69
Engine	.78	100	100	100
Structure	16.88	3.84	8.05	11.74
Propellant	198.92	19.21	40.30	58.70
Δvelocity (km/s)	3.72	3.72	7.40	10.0
TEI				
Structure	28.46	1.81	8.57	15.63
Propellant	183.13	9.00	42.86	78.14
Δvelocity (km/s)	1.62	1.62	6.50	10.0
MOI				
MEM	128.20	128.2	128.2	128.2
Structure	26.50	4.94	14.47	27.88
Propellant	694.71	24.70	72.36	139.41
Δvelocity (km/s)	2.76	2.76	6.50	10.0
TMI				
Probes	24.48	24.48	24.48	24.48
Structure	148.68	9.30	20.92	38.47
Propellant	3105.70	46.54	104.58	192.34
Δvelocity (km/s)	4.43	4.43	7.40	10.0
TOTAL MASS	4667.00	484.67	677.44	927.7

[a] 360 day outbound/200 day return/60 day stay.

[b] 1-yr round trip - 20-day stay.

[c] 3-month each way transit.

duration about equal to the U.S. Skylab experience, the requirements for closed environment life support systems (CELSS) and for artificial gravity might be reduced. As a result, the overall complexity of the ship design might be reduced.

Several possible types of advanced propulsive systems have been proposed over the last few decades. Low-thrust electric or variations of the nuclear-thermal rocket are not considered here because they are either under development or are already developed and are not advanced concepts. The truly conceptual designs can be grouped into beamed-power propulsion and improved specific-energy density concepts.

The beamed-power concept is one in which the power generation is performed at a fixed location and the energy to drive the spaceship is beamed to the ship's receptor in the form of lasers (optical or x-ray), microwaves, nuclear particles, or material pellets. These systems are usually low-thrust, high I_{sp} designs and operate over the duration of the trip. Consequently, the demands on beam divergence, pointing accuracy, and efficient power reception/conversion are very stringent. Although such systems should be considered, especially for transport of bulk material, greater potential is offered by the second group of engines within the next few decades.

The second group of systems relies on developing a propellant or propellant heating method with a high specific-energy (joule/kg). Consequently, these concepts depend on fission, fusion, or the mass-conversion of antiprotons ($\bar{p}$) as power sources to heat a working fluid. The development of these concepts must inherently deal with radiation of some type and thus must use massive engines. Furthermore, in some cases these engines will require the production of intense magnetic fields and stronger radiation resistant structural materials.

One of the earliest studies of using fission/fusion energy for space propulsion was the ORION concept utilized thermonuclear bombs detonated behind a massive pusher plate which ablated and drove the ship forward. Although the ORION concept used a simple propulsive method, copious amounts of neutrons and fission products were produced which made the concept unattractive.

Since the ORION study, the concept of using small, contained fusion microexplosions was developed. These systems employed an intense magnetic field to channel the charged reaction products and to contain the expanding plasma by flux compression. Usually, these explosions were assumed to be driven by photons, electron beams, or heavy ions. A recent study [1] estimated that the mass of laser driven or heavy ion driven ICF engines would be almost 500 tons.

The concept of using antimatter as a power source for propulsion has existed for decades.[2] Because antimatter annihilation has the highest specific energy of any reaction now known, the potential advantages of an antimatter propulsive system are very great. The obvious problems, however, are whether: (1) sufficient quantities of antimatter can be produced; (2) sufficient quantities can be conveniently stored for long periods; and (3) the products of the annihilation reaction can be converted efficiently into usable thrust.

INTRODUCTION TO ANTIPARTICLES

The concept of antiparticles began with the work of P. A. M. Dirac in the early 1930's on the dynamics of electrons.[3] This work for the first time needed the then-new, quantum mechanics with Einstein's relativistic kinematics. The need for this advance arose from atomic physics where it had recently been estimated that the electrons in an atom are moving in their orbits with velocities near the velocity of light. Dirac's new relativistic theory of electrons was an enormous breakthrough and explained a host of observed phenomena in an elegant and fundamental way. However, the new theory predicted the existence of a new particle in nature that was in every way the mirror image or antiparticle counterpart of the electron. In the mid-1930's, the anti-electron, that is the positron, was discovered.[4]

The tremendous success of the Dirac theory and its experimentally confirmed prediction of the existence of an antiparticle for the electron, touched off widespread speculation that the existence of antiparticles was a fundamental symmetry of nature. All particles have an opposite, an antiparticle. for protons there are antiprotons. For neutrons there are antineutrons, you have all the ingredients needed to make anti-atoms. Thus, it was speculated that there could exist a whole periodic table of anti-elements identical in every way to the familiar elements except that they are constructed of antiparticles. Soon the term antimatter was coined.

Although the existence of the antiproton was predicted in the 1930's, it was not until 1955 that its existence was experimentally observed. Chamberlain and coworkers[5] at the Lawrence Berkeley Laboratory had labored since the late 1940's to build a proton particle accelerator with enough energy to produce antiprotons. They knew exactly what they were after and tailored the accelerator design for the production of antiprotons. Their discovery of this new antiparticle rocked the world of physics and Chamberlain and Segre were awarded the Nobel Prize in physics for this observation. The award cited specifically the experimental confirmation of the particle-antiparticle symmetry in nature. This work opened the door for cosmologists and astronomers to ask in earnest if there were antimatter in our universe and stimulated a host of other investigations.

ANTIPROTON PRODUCTION

Since their discovery, the rate of antiproton production has increased by an order of magnitude every 2.5 years (on the average). This trend line is shown in Figure 1 where the relevant physics and detector technology are indicated as well.[5-22] The slope of this trend line is limited by funding and the available accelerator and magnet technology. The LEAR facility,[15-18] which recently came on-line at CERN, fits clearly on the trajectory, as does a proposed facility at Los Alamos.[20,21] The early part of this trend line was driven by the advent of the zero gradient synchrotron (AGS)[9] at the Brookhaven National Laboratory. In fact, most antiproton production in this era actually exceeds the trend line which is drawn on a conservative trajectory. The present and future production rates will be driven by a new technology, stochastic and electron cooling.[23] The facility at the Fermi National Accelerator Laboratory (FNAL)[19] is already considerably above the trend line. In addition, a practical antiproton factory, using existing magnet and accelerator technology, could be built by the 1990's and would produce 100 to 1000 times more antiprotons than the conservative Los Alamos proposal. This possible factory is still further above the trend line, which shows that the projected limits of the new cooling technology are not properly indicated. Actual limits could be considerably higher. Nevertheless, if the conservative trend line is followed, the annual production of antiprotons could exceed a gram by the year 2010.

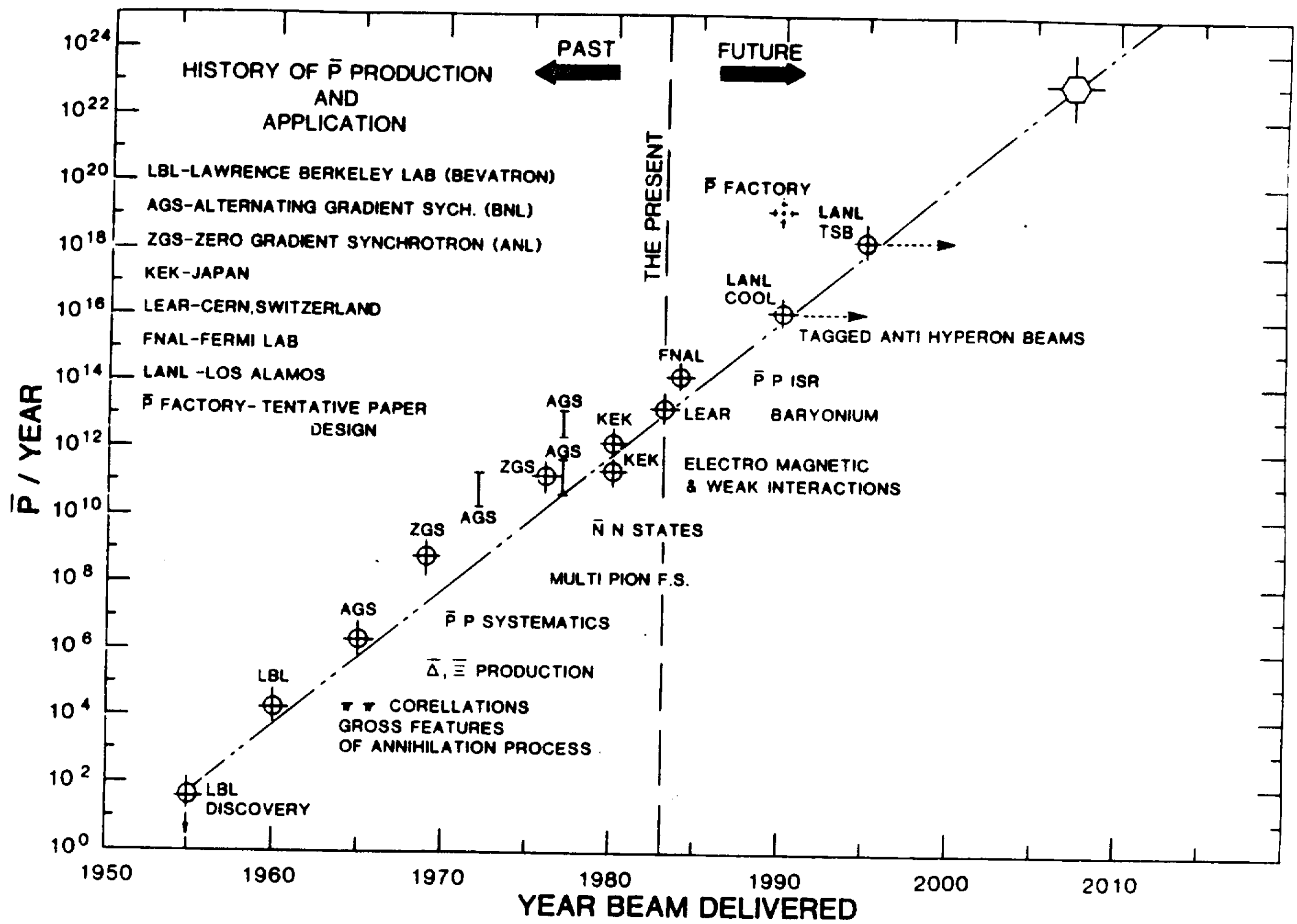

Fig. 1. Annual antiproton production versus year for most high-energy physics facilities around the world. The circled points represent the published flux value; the vertical bar indicates the range of fluxes cited in the literature (Refs. 5-22). The point labeled $\bar{p}$ factory represents a practical design using existing magnet and accelerator technology. The physics of interest for each era is also noted.

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The advent of the new cooling technology has already made possible major advances in high energy physics. These same techniques offer uniquely exciting possibilities for ultralow energy physics as well. Through a combination of deceleration stages, antiprotons produced at several GeV (where the production is at a maximum) can be made available for experiments at thermal velocities. This availability opens many new avenues of basic and applied research in atomic, condensed matter and nuclear physics.

Aside from the success of the new cooling technology in antiproton production, there is little understanding of the fundamental production mechanism. A simple view of the production of antiprotons has a high energy proton incident on a nucleon at rest in, for instance, a liquid hydrogen target. Such an initial state can reach a multitude of possible final states ranging from simple elastic scattering to multiple pion and kaon production, depending upon the incident beam monentum. However, let us consider only those final states which produce antiprotons. To conserve baryon number and charge, antiprotons are produced as part of a proton-antiproton pair. The minimum beam momentum required for this reaction is 6.5-GeV/c, whereas the likelihood for production increases rapidly with increasing momentum. Typical antiproton production facilities for basic research use incident beam energies in excess of 20 GeV. Usually, these facilities use targets of beryllium, carbon or tungsten instead of liquid hydrogen. This simplifies the production system structure and leads to slightly different kinematic properties of the distribution of antiprotons emerging from the target. There have been a great number of measurements of antiproton production from nuclear targets, although only over a limited range of antiproton momentum and production angle.

Despite the lack of fundamental understanding of the production process, several empirically derived production cross section formulations describe the limited data available. These empirical formulations have been used to design the collection facilities at CERN and FNAL. Neither of these facilities were designed originally with antiproton production or collection in mind. Their collection facilities were added onto the existing accelerator systems. Nevertheless, the antiproton production capabilities of these facilities is impressive. At

CERN or FNAL, 10^{13} -10^{14} antiprotons can be produced, with 10^{15} per year in the near future.

Two other facilities are currently being planned in the free world for producing, among other particles, antiprotons: TRIUMF in Canada and a facility at the Los Alamos National Laboratory. The antiproton production rates at these facilities could far exceed those currently available at CERN and FNAL. However, even these facilities are not optimized solely for antiproton production and do not exploit fully the available magnet and accelerator technology. These and all previous antiproton facilities represent the very best that could be done with a fiscally constrained basic research budget. The current Los Alamos plan, for example, is a $300M project, not including an antiproton collector and cooler. If the fiscal constraint were lifted for the design of an antiproton factory, several orders of magnitude more antiprotons per year could be produced using existing technology. However, before this increase in production can be cooled and accumulated, very significant progress needs to be made in accumulator/cooling technology. In addition, before the milligram-to-gram size quantities, projected for the next decade and beyond, can be produced, very significant progress in accelerator technology needs to be made as well. Increasing the production/cooling rates is a high priority task at antiproton facilities around the world. Rapid progress in these areas can be expected in the short term. Thus, technological research and development here in the US should proceed on the assumption that such quantities of antiprotons will be available in the coming decades.

The only facility in the world today that is capable of producing low energy antiprotons is at CERN. The facility at FNAL accumulates antiprotons at high energy, and at present has no low energy capability. The possibility of developing a low energy capability at FNAL is probably the best option for a low energy antiproton facility in the United States before 1990. After 1990, a true antiproton factory is needed. Without such a facility, by the next decade, the United States will be a third world country in antiproton technology, behind the Soviet Union, Switzerland, and Canada.

STORAGE OF ANTIPROTONS

At the present time the particle physics community stores a significant number of antiprotons for several tens of hours for basic research on particle dynamics at very high energies. The storage technique used is electromagnetic confinement in very large rings inside which the antiprotons are circulated or accelerated to the desired energy. Although well-suited to the requirements of many applications in basic research, this type of storage is not readily adapted to the applications we envision. We have considered two general types of storage: Bulk storage, in which antimatter at low temperature is stored in a high vacuum, and dispersed storage, in which the antimatter is stored in a uniform mix with normal matter. Whether in bulk or dispersed storage, the antimatter can be charged, as in the case of antiprotons or it can be neutral, as in the case of antihydrogen atoms.

The discovery of the positron in 1932[4] started the theoretical and experimental work on the fundamental interaction between matter and antimatter. The discovery of the antiproton in 1955[5] triggered a series of cosmological studies investigating the signatures and consequences of antimatter in our universe.[24-27] These studies addressed the basic symmetry between the existence of both matter and antimatter on a cosmological scale. A model for the separation of matter and antimatter was presented to explain the apparent absence of antimatter in our local space.[24] This early work marked the beginning of the quantification of the matter-antimatter interaction problem. Later work by Morgan and Hughes[28] pointed out, for the first time, the importance of atomic scale processes in antihydrogen-hydrogen collisions. Morgan and Hughes calculated the cross section for annihilation as a function of temperature. This cross section together with the number density of particles, determines the average lifetime of the plasma. For very long lifetimes, very low densities must be used (10^{-4} to 10^{-10} per cm^3).

The principal operating feature in these calculations is the long-range van der Waals force, which is attractive for normal matter-matter mixtures and is still attractive for matter-antimatter mixtures. As the matter-antimatter atoms or molecules draw more closely together, the interaction potential grows increasingly more attractive, until finally the protons and antiprotons annihilate along with the electrons and positrons. With normal matter-matter interactions, as the two atoms or molecules draw more closely together, the potential also becomes more strongly attractive until the two objects are close enough to start exchanging electrons. At this point, a repulsive exchange force overwhelms the attractive force and the two objects can get no closer.

Let us consider what is required to store antimatter. Stated simply, the antiprotons (and any positrons) must be kept away from their normal matter counterparts to prevent annihilation for timescales of a year or longer. For the bulk storage of antimatter, contact with the confining walls must be eliminated, whereas for dispersed storage, a metastable state for the antimatter within the normal matter matrix must be found. Consider the assumptions that led to the result that the van der Waals force is attractive. Firstly, it is assumed that the anti-atom and the atom are interacting as free particles, as in a dilute gas, uninfluenced by nearby neighbors. Also, it is assumed that the atoms are in a ground state which is assumed spherically symmetric, without any electromagnetic moments higher than the monopole charge. Finally, it is assumed that there are not external electric or magnetic fields.[29] Changing any of these basic assumptions can lead, in principle, to a repulsive barrier.

The scale of the barrier needed to confine the antiprotons can be estimated by treating the confinement as a one-dimensional barrier penetration problem.[30] The transmission coefficient for such a barrier should be in the range 10^{-30} - 10^{-35} in order to realize long-term storage of gram-like quantities. The calculation reveals that transmission coefficients in this range can be obtained with barrier heights of about 0.5 eV and widths of 2 to 4 angstroms for thermal antiprotons (10 - 100K). The scale set by these results are atomic in size. Thus, much of our effort in searching for a storage medium for antimatter will necessarily be concentrated in atomic and condensed matter systems.

A simple and obvious way to prevent antiprotons from impinging upon the walls of a storage vessel is to electrically charge the walls so as to repel them. Storage devices of exactly this sort have been intensively studied both theoretically and experimentally for the confinement of normal matter ions.[31] All of this "ion trap" work is directly applicable to the storage of antiprotons. Briefly, the charged particles are stored in a volume defined by a combination of electric and magnetic fields or in an inhomogeneous RF field. In addition, techniques for cooling the confined ions to very low temperatures have been developed.[32]

To explore any of the atomic or condensed matter storage approaches, a thermal source of antiprotons is required. Because of the cooling capability of ion traps, these devices can serve as an intermediate technology allowing for the study of more advanced concepts. More importantly, however, ion traps could allow for the storage of significant quantities of antiprotons today. The practical limit on storage of this type in sensibly dimensioned equipment is of order 10^{15} - 10^{17} antiprotons. This not only represents more antiprotons than is currently being produced yearly at existing facilities, but it also represents an engineeringly significant amount of energy (0.3 - 30.0 megajoules).

APPLICATIONS

The capability to store large numbers of antiprotons at thermal velocities will open many avenues of basic and applied research. The potential applications that we envision utilize the very high specific energy characteristic of antimatter annihilation. The specific energy in joules per kilogram for a variety of exoergic reactions is shown in Table 2. The fact that antiproton annihilation has specific energy 10^8 times chemical values and about 10^3 times fission/fusion reactions, indicates the enormous potential of antiprotons as an energy source for space based prime power and propulsion applications where mass is a principle consideration.

Because the energy release modes of antiproton annihilation are vastly different than any other energy source, the questions confronting designers of antiproton propulsion or power sources must be approached from fundamental viewpoint. Although in their infancy, several propulsion system concepts have been discussed.[33-37]

One concept which has not been discussed but which may offer a near term potential is the Solid Core Thermal Rocket (SCTR). The SCTR would utilize the antiprotons by stopping all of the annihilation products in a solid core of high-melting-temperature material such as tungsten. The core is honeycombed to allow the heat transfer to the propellant. Such a

TABLE 2

SPECIFIC ENERGY COMPARISON

Source	Specific Energy (joule/Kg)
Chemical	
gasoline + air	9.1 e06
hydrogen + flourine	1.3 e07
hydrogen recombination	2.2 e08
metastable helium	4.8 e08
Fission	
U-235	8.2 e13
Fusion	
D(t,n)4He	3.4 e14
D(d,n)3He	7.9 e13
D(3He,p)4He	3.5 e14
Antiproton Annihilation	
$\bar{p}$ + p	9.0 e06

concept is similar to the nuclear rockets developed during the NERVA program and could possibly utilize many of the non-nuclear components, such as liquid hydrogen (LH_2) turbo pumps, already tested. A schematic diagram of the small nuclear rocket engine (SNRE) designed in 1971 is shown in Figure 2. This engine would have produced about 16000 lb of thrust and would have weighed about 5887 lb. The figure shows the layout of the liquid hydrogen transport lines, valves, and pumps which were tested in the NERVA program. Preliminary calculations indicate that a tungsten cylinder which has been sized to stop most of the $\bar{p}$ annihilation products would be slightly smaller than the nuclear reactor core designed for the SNRE. These calculations included the 36% void fraction for the hydrogen flow channels used in the SNRE. A $\bar{p}$-NERVA engine based on the most thoroughly tested nuclear rocket, designated NRX, would have a thrust of 4.4×10^5 N (100,000 lb), a power level of around 2700 MW, a mass of near 11000 kg, an I_{sp} of 1100 s, and a mass flow of antiprotons of around 13 μg/s. Such an engine would require about 400 metric tons of material in LEO to accomplish the baseline manned Mars mission--a factor of 4.5 times less than a chemically propelled system.

Another engine concept utilizes a reaction chamber filled with high pressure gas into which the antiprotons are deposited. The charged annihilation products are trapped by an intense magnetic field, slow down, and heat the gas for expulsion. This engine concept has the advantage of adjusting the ratio of antimatter to produce a wide range of I_{sp} depending upon the mission. The possible effects of pion and muon thermalization times, wall losses, reaction chamber structural requirements, and losses of pions or muons due to nuclear reactions or decay, need to be evaluated after more fundamental data have been collected, and will require complex computational studies.

The amount of antimatter required by either concept will depend upon the mission delta V requirements. Typical missions such as launch from Earth's surface, orbital transfer to GEO, or a mission to Mars will probably require between tens to hundreds of milligrams. The ship's mass ratios for these missions would be about 3 to 10.

Other results presented during this workshop indicate that (1) artificial gravity may be required on the Mars-mission ship to alleviate bone and muscle mass loss, (2) radiation dose rates of about 50 rem/yr

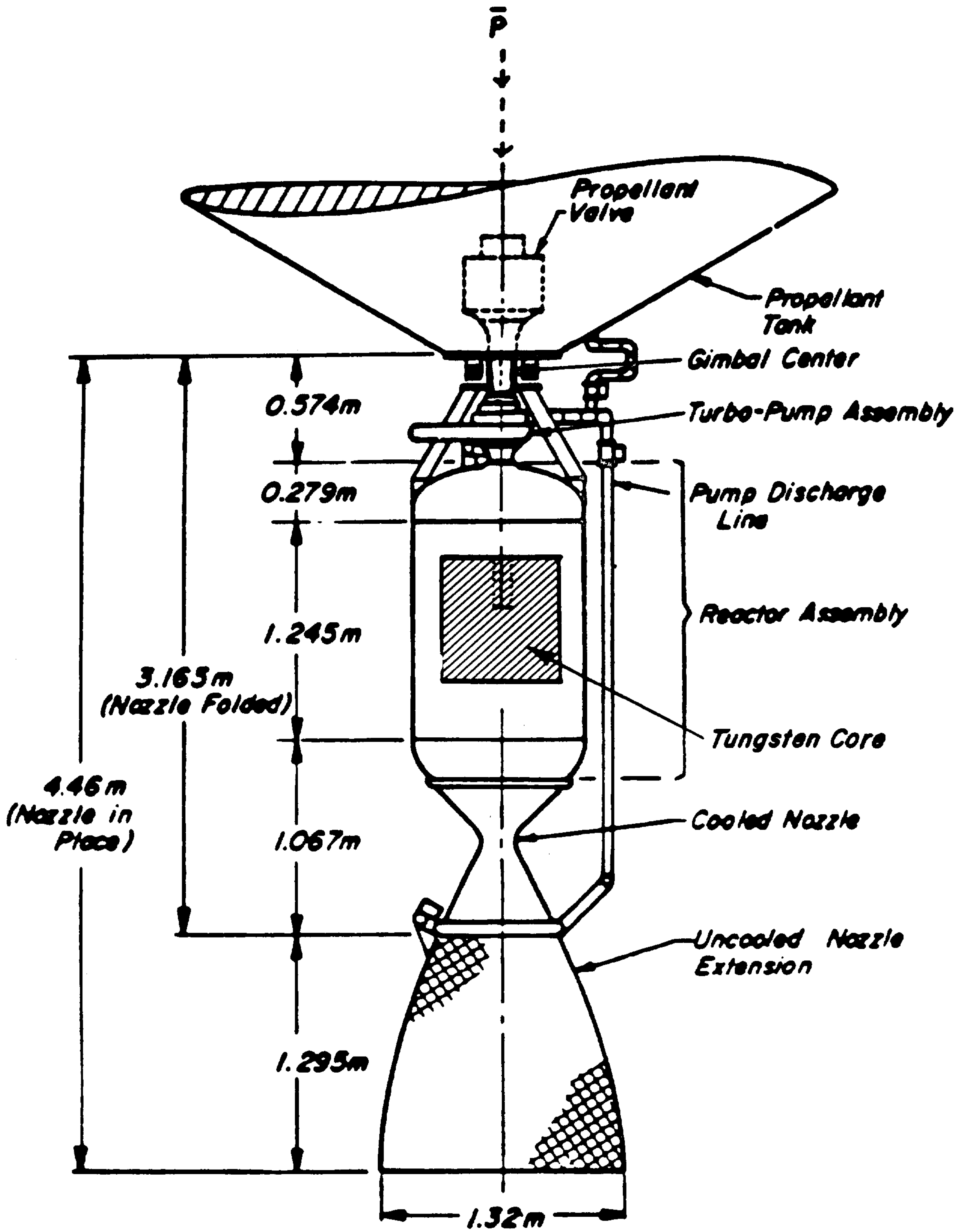

Fig. 2. Schematic diagram of the Small Nuclear Rocket Engine designed during the NERVA program. The nuclear reactor core has been replaced with a possible configuration of the metal-honeycomb used to convert the antimatter annihilation energy into heat.

in interplanetary space may limit missions to 3 yrs or less, i.e. Mars and Venus only for chemically propelled manned systems, and (3) confinement times of over a year in a spacecraft may induce psychological difficulties. Although these problems may be tenable by more complicated and massive ship design, the use of an antimatter engine which could reduce trip times to under a year could also alleviate most of the problems.

In general, the antiproton powered engine may allow low mass-ratio ships and/or fast transit-time missions to become possible. These two characteristics may not be simply enhancing but actually enabling to certain space missions such as planetary exploration.

ENHANCEMENT

The specific cost of production of antimatter (dollars per unit mass) is a convenient but misleading quantity. A more significant quantity is the dollars per unit energy. Reduction of these ratios has always been assumed to depend on improving the production and collection efficiency of the antimatter factory accelerator. Use of the latter ratio, however, shows that improvements can be made if the energy output for each incident antiparticle is increased or amplified.

One possibility is to consider the antiproton as a stable repository of negative muons. An average $p\bar{p}$ annihilation will produce about 1.45 negative pions with an average energy of 250 MeV. If the pions can be either trapped in magnetic field or quickly thermalized by collisional losses, then the negative muons (μ^-) resulting from the pion decay may be generated in a small volume. By thermalizing these muons in a volume containing a mixture of gaseous deuterium and tritium, fusion of the DT atoms can be catalyzed.[38-42] Recent measurements of D μ T molecular formation rates[43] and of other factors inherent in $\bar{\mu}$ catalyzed DT fusion have observed up to 180 fusions per muon. The resonant molecular-formation theory which accounts for the observations predicts that up to 300 fusions per muon could be induced in DT mixtures at appropriate density and temperature. Thus, an upper limit of about 7.8 GeV in fusion energy could be released per antiproton in addition to the 1.8 GeV of annihilation energy--more than a factor of 5 enhancement. Clearly, losses due to pion capture and inter-actions, muon decay during thermalization, and muon-wall interactions, as examples, will reduce this upper limit in an operating system. Efforts to estimate the magnitude of different loss factors and of a possible reactor geometry are currently underway.

Another method of producing fusion energy using antiprotons is inertial confinement fusion (ICF). This technique relies on stopping the antiprotons in a thin, uranium shelled capsule containing DT gas. The stopped antiprotons annihilate on the uranium nuclei and induce fission. The localized deposition of the fission energy ablates part of the shell and implodes the capsule. Early calculations show that more than 10 GeV[9] could be released, with much higher gains possible. Experiments characterizing the $U(\bar{p},f)$ reactions are underway at CERN with the ultimate goal of investigating antiproton- produced implosions.[44] The major attraction of the ICF technique is that the incident antiproton energies could be a few keV or less so that the required accelerators would be small. Thus, depending upon the mass of the antiproton storage device, low mass ICF reactors might be possible. Evaluations of pulse structure, implosion symmetry, and optimum capsule design are required, and significant work in those areas can be performed with currently existing codes.

SUMMARY AND CONCLUSIONS

Since their discovery in 1955, antiproton production rates have increased by an order of magnitude every 2.5 years. The advent of the new cooling technology could make the production rates rise even faster. Nevertheless, if the conservative trend is followed, a gram of antiprotons could be produced yearly by the year 2010. Many of the applications we envision for antiprotons require only milligram-size quantities. These applications are in the area of energy sources for prime power and propulsion for space-based systems where high-energy density is of principal importance. Storage of antiprotons can be accomplished in sensibly dimensioned equipment using ion traps for quantities up to 0.1 micrograms. Higher density storage techniques have been investigated theoretically and require experimental work to make progress. For this work, the ion trap storage device will serve as an intermediate technology, supplying a thermal source of antiprotons. Antiproton technology will be upon us in the coming decades. Now is the time to consider what technical steps are required to enable the concept of antiproton power sources to be put on a more scientific basis.

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